Appendix D

Sediment Concentration and Discharge Computations

APPENDIX D

SEDIMENT CONCENTRATION AND DISCHARGE COMPUTATIONS

Equations for Suspended Sediment Concentration (SSC) as a function of turbidity are developed using linear regression methods with SSC as the dependent variable and turbidity as the independent variable. The equations developed are site specific and are typically based on data collected over a wide range of streamflows and basin conditions. Many factors may influence the SSC–turbidity (SSC-T) relationship for any given site, such as the geology of the watershed, soils, vegetation, slope, aspect, and land use (Lewis, et al., 2002).

The SSC-T relationship is also affected by the effects of sediment loading over time as exhibited downstream of reservoirs. In general, sediment discharge from reservoirs tends to be higher in fine sediment, as the coarser fraction settles out in the reservoir pool.

To provide estimates of SSC in the South Fork McKenzie river below Cougar reservoir, the Corps used data from the USGS North Santiam River Basin Suspended-Sediment and Turbidity Study (Urich, et al, 2002). SSC-T relationships were developed for five sites in the North Santiam basin, and provided by the USGS. Three sites were located on tributary streams draining Detroit reservoir and two sites were located on the North Santiam below Detroit reservoir. Figure 1 shows the location of the sites.

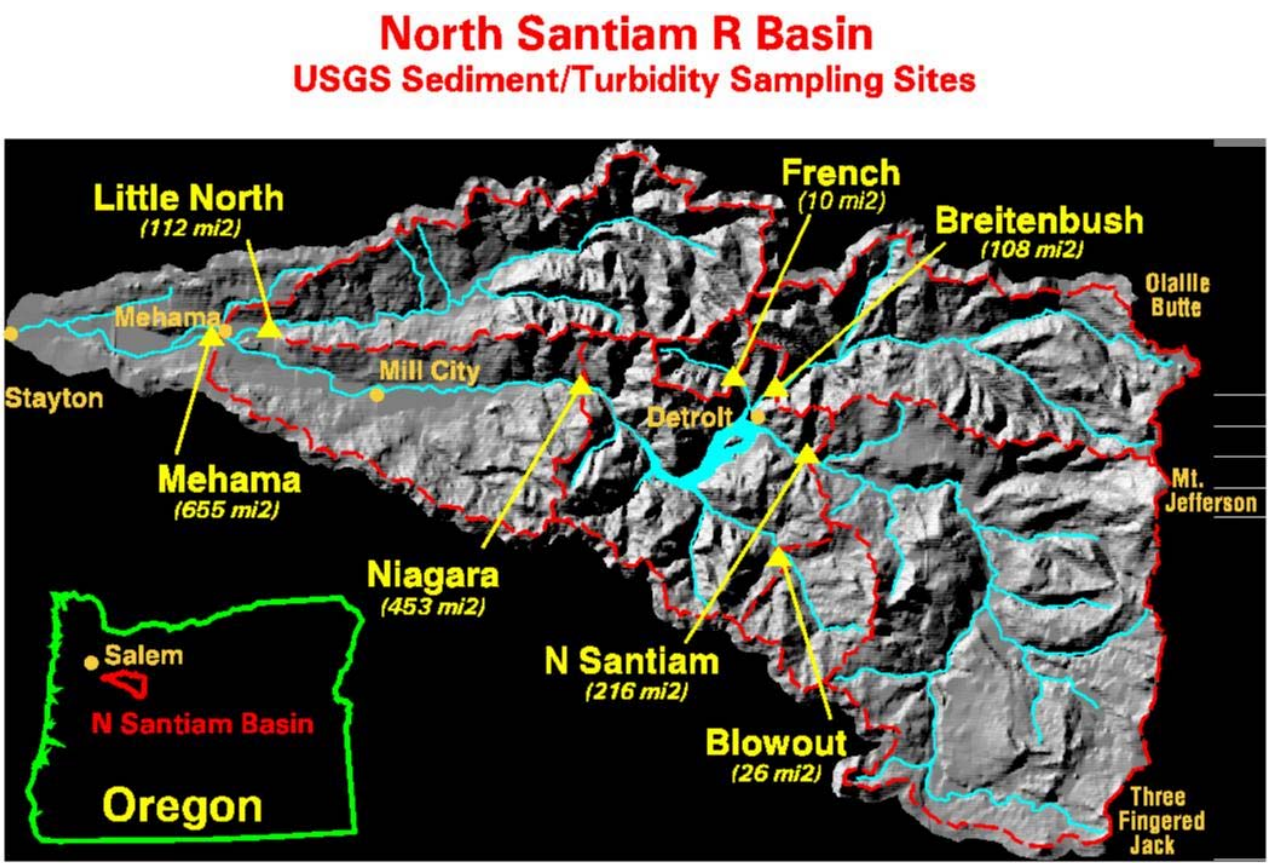

Figure 1- SSC-Turbidity data collection sites - North Santiam River Basin Suspended-Sediment and Turbidity Study. Image source - http://oregon.usgs.gov/projs_dir/or00311/

After evaluation of the five SSC-T relationships provided (Table 1), the Corps used the SSC-Turbidity relationship at Mehama, OR (USGS gage 14183000) to develop its SSC and sediment discharge estimates for the South Fork McKenzie river below Cougar reservoir.

Table 1 - North Santiam Basin SSC-T relationships (provided by USGS)

Site	Description	Regression Equation	R^2	Standard Error (Original Units)
North Santiam below Boulder Cr	Input to Detroit Reservoir	$SSC = 1.70\ T^{1.04}$	0.907	34.3
Breitenbush River above French Cr	Input to Detroit Reservoir	$SSC = 1.85\ T^{0.988}$	0.927	39.6
Blowout Cr Near Detroit	Input to Detroit Reservoir	$SSC = 1.44\ T^{1.08}$	0.915	30.8
North Santiam at Mehama, OR	Below Detroit Reservoir	$SSC = 1.90\ T^{0.752}$	0.888	24.5
North Santiam at Niagara, OR	Below Detroit Reservoir	$SSC = 2.00\ T^{0.633}$	0.598	15.3

The Mehama, OR location was selected because it represented a site located below a reservoir (Detroit), and because of the similarity in geology of the North Santiam and South Fork McKenzie watersheds. Suspended sediment samples taken (CUGRSD1- 4) at the USGS gage at Rainbow, OR during the drawdown were compared with the turbidity readings taken at the time of the sampling. These samples were plotted with the Mehama data set. To account for possible sampling error due to the sampling method, error bounds representing plus or minus 25 percent were applied to the five samples used for comparison (Figure 2). The plotting position of the drawdown samples fit well within the Mehama regression.

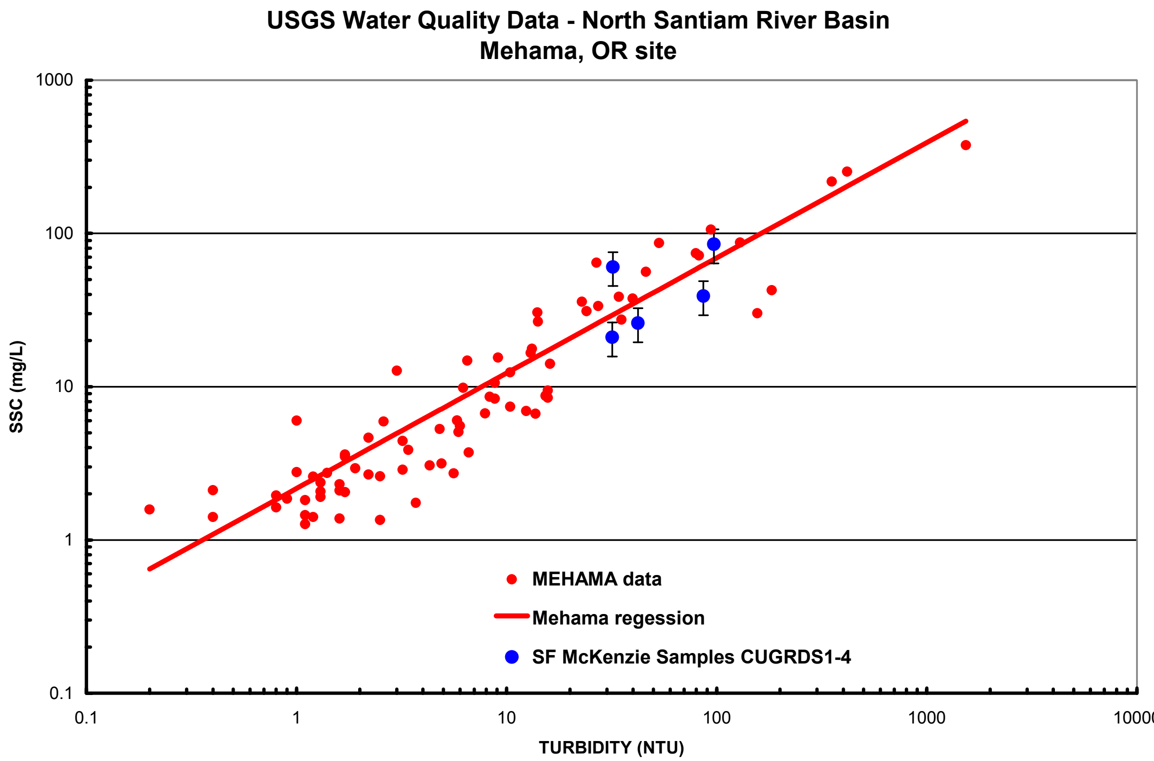

Figure 2 - USGS Water Quality Data, Mehama, OR, South Fork McKenzie river Samples CUGRDS1 - 4.

The Niagara SST-T relationship was not used because of the lower R^2 value suggesting a poorer correlation between SST-T at that site then at Mehama. This was in part due to a smaller data set at Niagara. The SST-T regressions for the two sites below Detroit were found to be similar, as were the three sites above Detroit reservoir.

Because the SSC-T relationships are watershed and site specific, use of the Mehama data to estimate SSC and sediment discharge below Cougar Reservoir provides at best, a gross estimate.

To estimate the SSC concentrations at the unusually high turbidity levels observed during the tunnel tap, laboratory analysis was conducted on reservoir sediment samples collected from inside Cougar reservoir (Sobecki, et al 2003). The reservoir sediment was suspended at several different concentration levels. Turbidity was measured at the different concentrations to define the SSC-T relationship at turbidity levels above 200 NTU.

For Mehama, OR the SSC-T relationship is given by:

(1) $SSC_M = 1.90 \cdot T^{0.752}$

where SSC_M = Suspended sediment concentration in mg/liter
T = Turbidity in NTU (Nephelometric Turbidity Units)

For high turbidity (greater than 200 NTU) the SSC-T relationship developed by laboratory analysis is given by:

(2) $SSC_L = 0.55 \cdot T + 83.45$

where SSC_L = Suspended sediment concentration in mg/liter
T = Turbidity in NTU (Nephelometric Turbidity Units)

Estimates of suspended sediment concentration are based on turbidity observed at the SF McKenzie near Rainbow, OR USGS gage, number 14159500 for SF McKenzie River below Cougar Dam are given by Eqs. (3) & (4):

(3) $SSC_{CGRO} = 1.90 \cdot T_{CGRO}^{0.752}$ Turbidity range 0 to 200 NTU, Standard Error = 24.5 mg/liter

(4) $SSC_{CGROH} = 0.55 \cdot T_{CGRO} + 83.45$ Turbidity range above 200 NTU

where SSC_{CGRO} = Estimated suspended sediment concentration in mg/liter below Cougar Dam
SSC_{CGROH} = Estimated suspended sediment concentration in mg/liter below Cougar Dam (turbidity above 200 NTU)
T_{CGRO} = Turbidity in NTU, measured at USGS gage

SUSPENDED SEDIMENT CONCENTRATION ESTIMATES FOR TUNNEL TAP AND DRAWDOWN EVENTS - SF MCKENZIE RIVER NEAR RAINBOW, OR. (BELOW COUGAR DAM) USGS GAGE ID 14159500

Estimates of suspended sediment concentration immediately below Cougar Reservoir are computed for four separate time periods during Spring 2002, for use in assessing the effect of high turbidity on fishes. The significance for selection of these time periods is discussed in the main body of the Supplemental Information Report.

The four time periods are:

1. 2/23/2002 ~ 1300 turbidity measurement below the reservoir - 1358 NTU (point estimate)
2. 2/23 to 2/27/2002
3. 4/09 to 6/06/2002
4. 4/28 to 5/30/2002

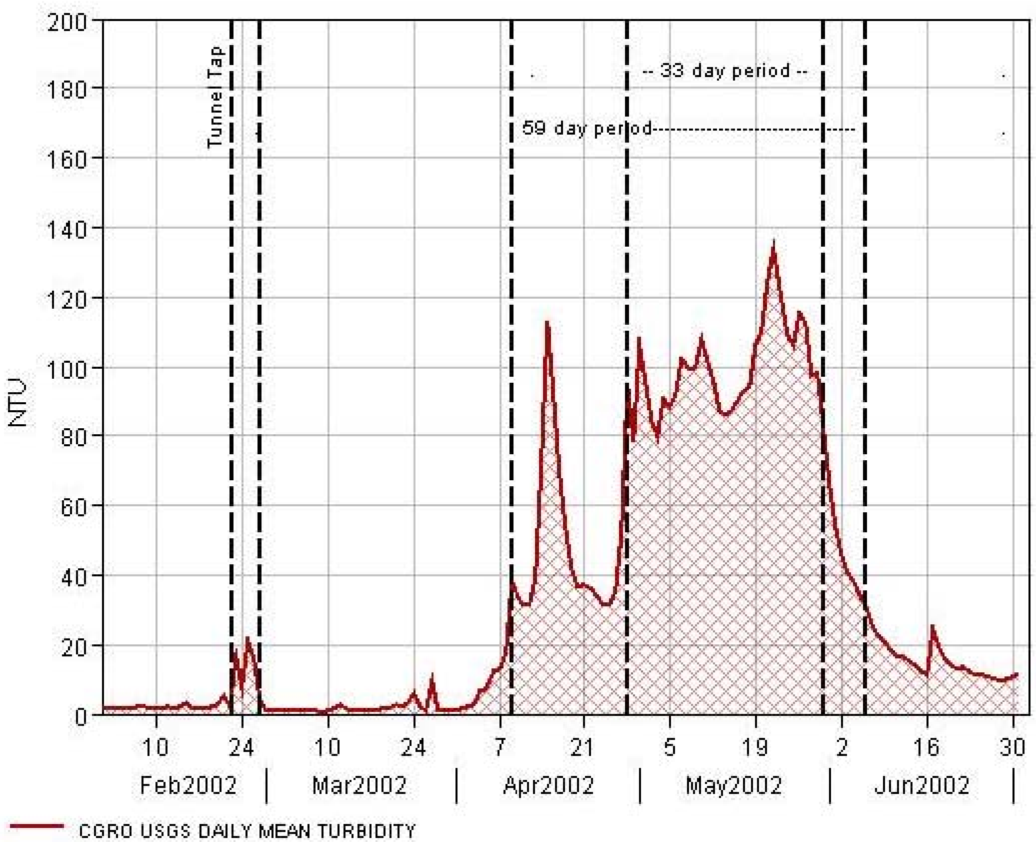

Figure 3 - Mean daily turbidity values, SF McKenzie River near Rainbow, OR. 2/01 - 7/01/2002

1. Point estimate - 1358 NTU

Using Eq (4) $SSC_{CGROH} = 0.55 \cdot T_{CGRO} + 83.45$

$$SSC_{CGROH} = 830.35 \frac{mg}{liter}$$

2. **5 day period 2/23 to 2/27/02**

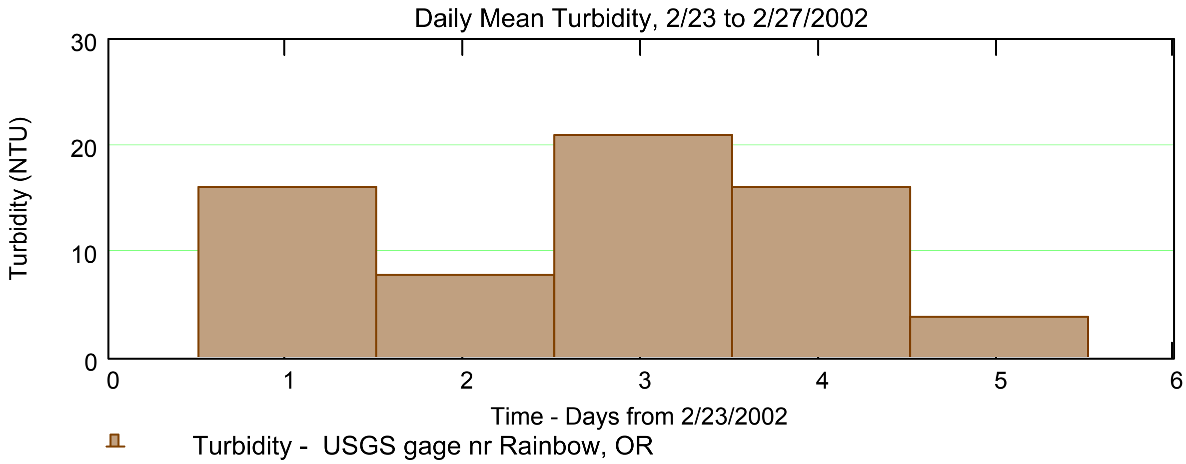

Figure 4 - Mean daily turbidity values, February 23 to 27, 2002

Using Eq (3) $SSC_{CGRO} = 1.90 \cdot T_{CGRO}^{0.752}$

Average turbidity over 5-day period $\mathrm{mean}\left(T_{CGRO}\right) = 12.9\ \mathrm{NTU}$

Average suspended sediment concentration over 5-day period $\mathrm{mean}\left(SSC_{CGRO}\right) = 12.7\ \frac{mg}{liter}$

3. 59 day period 4/09 to 6/06/2002

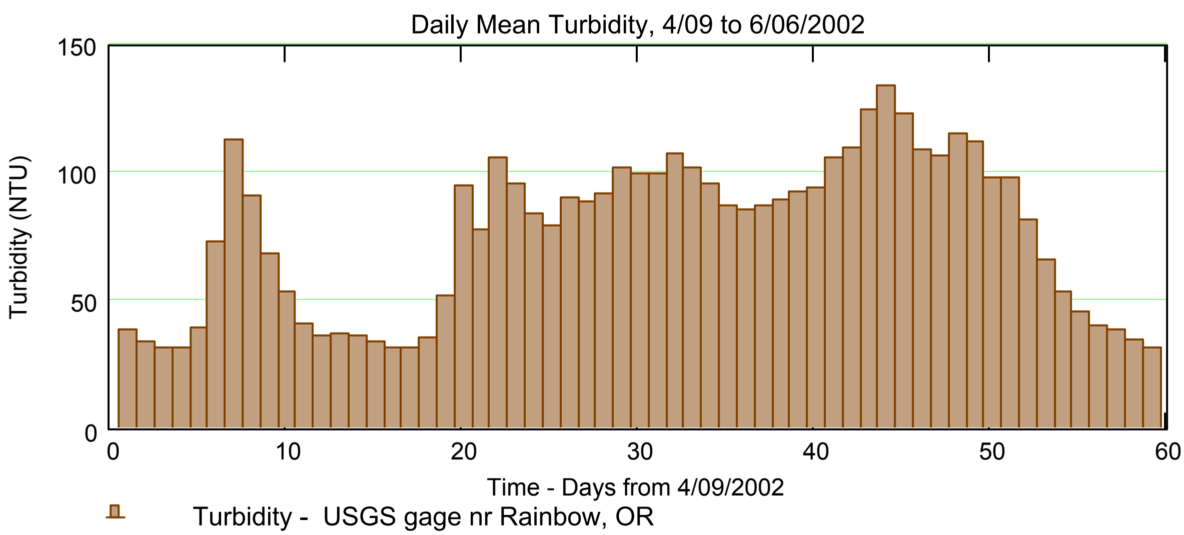

Figure 5 - Mean daily turbidity values, April 9 to June 6, 2002

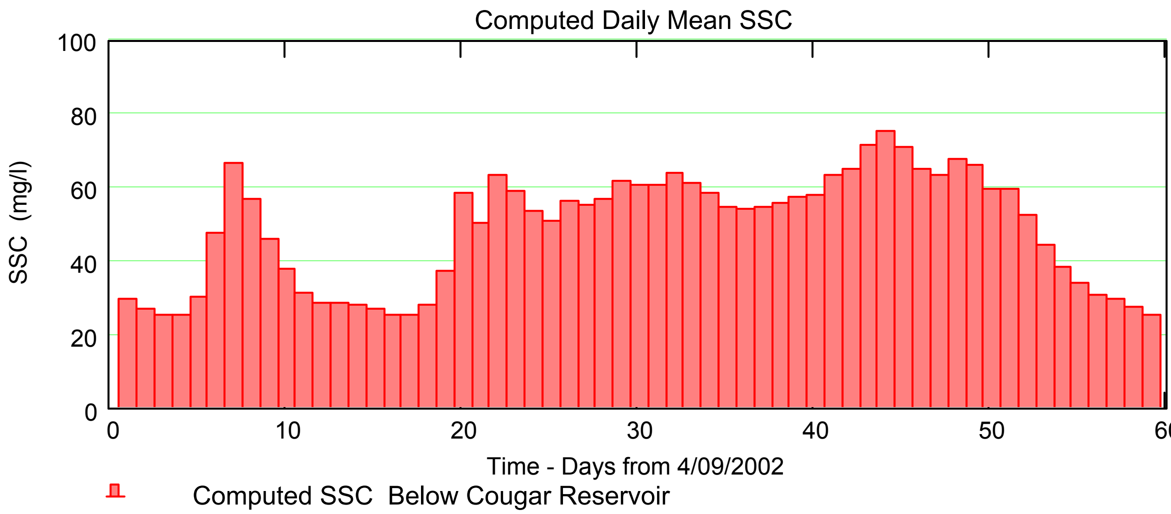

Figure 6 - Mean daily computed SSC April 9 to June 6, 2002

Using Eq (3) $SSC_{CGRO} = 1.90 \cdot T_{CGRO}^{0.752}$

Average turbidity over 59-day period $\quad \text{mean}\left(T_{CGRO}\right) = 76.1 \text{ NTU}$

Average suspended sediment concentration over 59 day period $\quad \text{mean}\left(SSC_{CGRO}\right) = 48.5 \frac{\text{mg}}{\text{liter}}$

4. 33 day period 4/28 to 5/30/2002

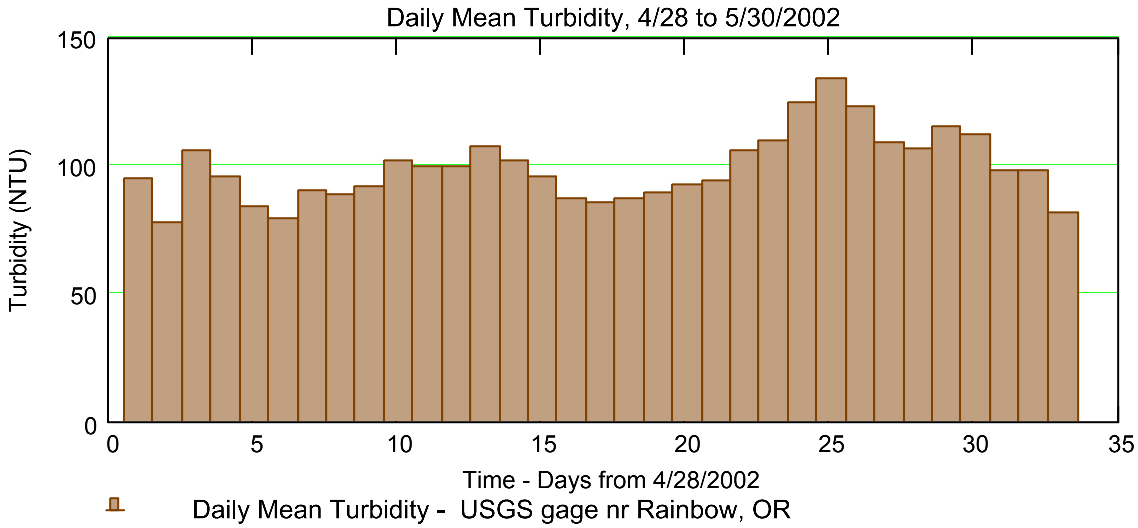

Figure 7 - Mean daily turbidity values, April 28 to May 30, 2002

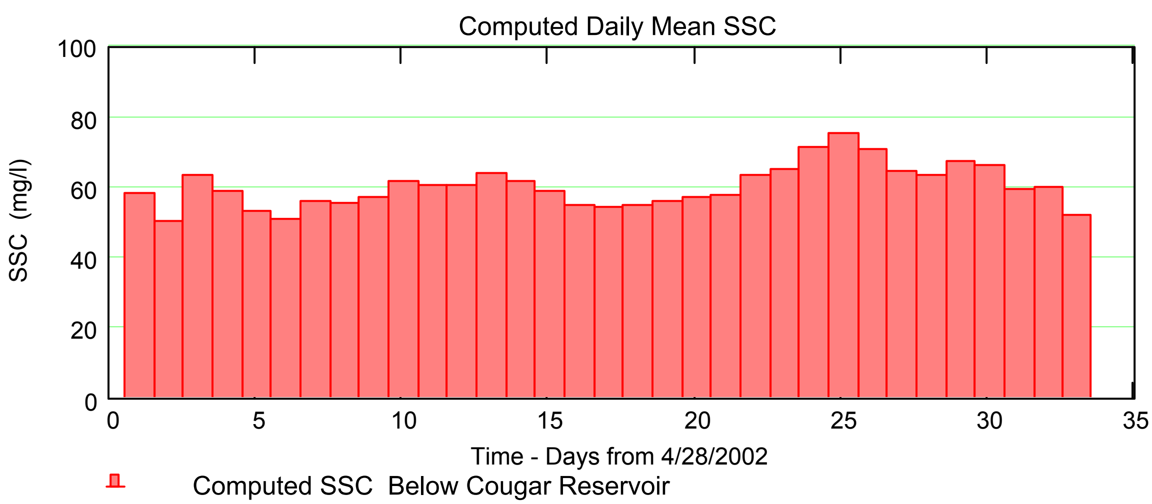

Figure 8 - Mean daily computed SSC, April 28 to May 30, 2002

Using Eq (3) $SSC_{CGRO} = 1.90 \cdot T_{CGRO}^{\;0.752}$

Average turbidity over 33-day period $\qquad \mathrm{mean}\left(T_{CGRO}\right) = 99\ \mathrm{NTU}$

Average suspended sediment concentration over 33-day period $\qquad \mathrm{mean}\left(SSC_{CGRO}\right) = 60.1\,\frac{\mathrm{mg}}{\mathrm{liter}}$

SEDIMENT DISCHARGE CALCULATIONS

Using the SSC-T relationship at Mehama, OR the estimated sediment discharge in tons from Cougar reservoir is computed for the period 4/01 to 7/01/2002

Daily mean sediment discharge is computed by the following equation:

(5) $q_S = Q \times c_S \times 1\text{day}$

where q_S - is sediment discharge in tons

Q - daily mean discharge in cubic feet per second

c_S - computed daily mean SSC in mg/liter

For Cougar reservoir, the daily mean discharge at USGS gage number 14159500 for SF McKenzie River below Cougar Dam is used to compute the sediment discharge below the dam.

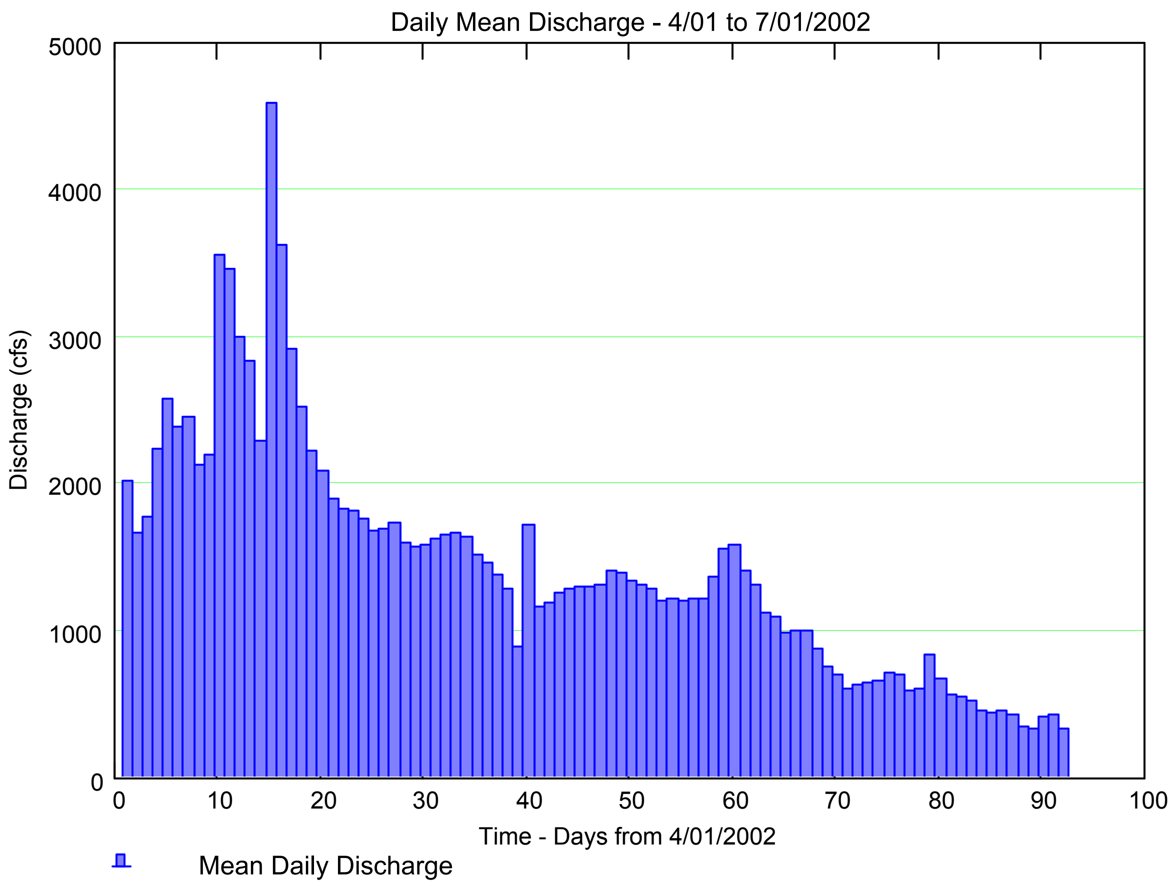

Figure 9 - Mean daily discharge, S. Fork McKenzie near Rainbow, OR, April 1 to July 1, 2002

Daily mean SSC is computed by Eq (3) $SSC_{CGRO} = 1.90 \cdot T_{CGRO}^{0.752}$

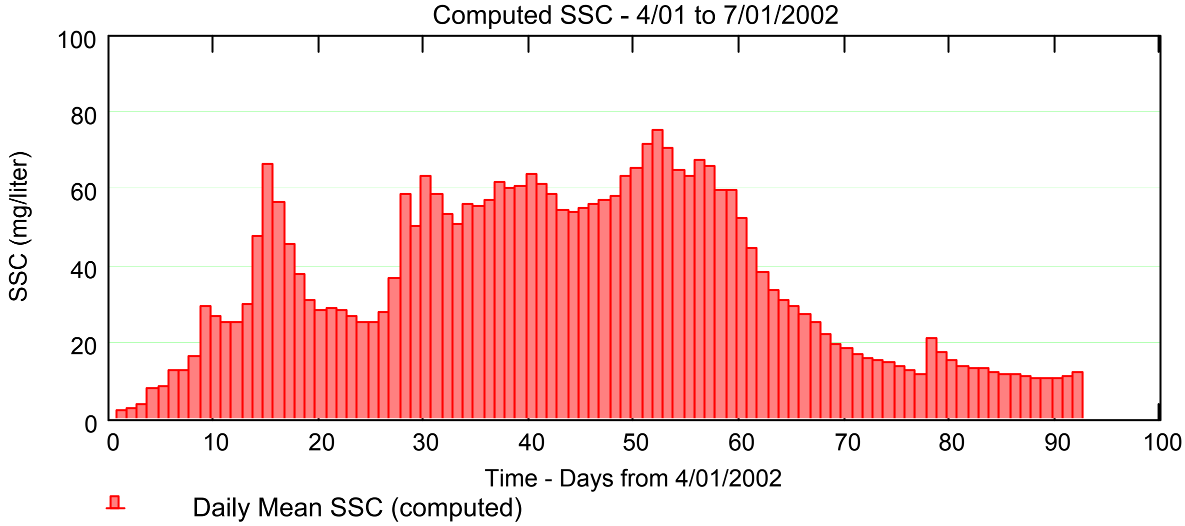

Figure 10 - Daily mean computed SSC, April 1 to July 1, 2002

Using daily mean SSC computed by Eq (3), sediment discharge is computed using Eq (5) $q_s = Q \times c_s \times 1\text{day}$

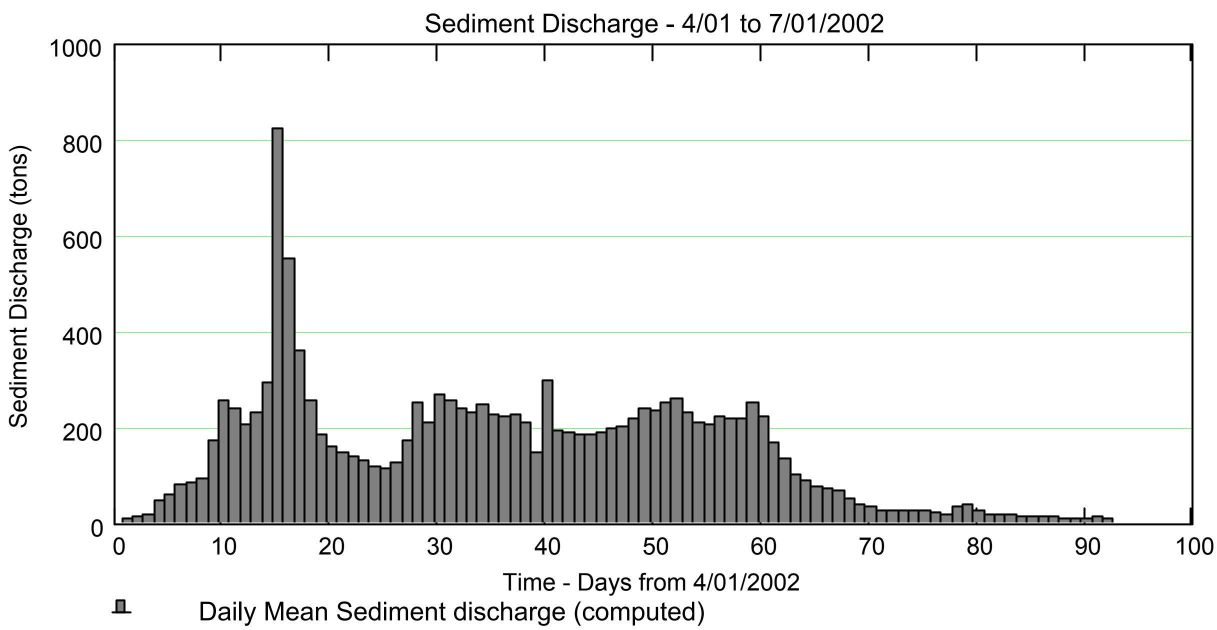

Figure 11 - Daily mean computed sediment discharge in tons from Cougar reservoir, April 1 to July 1, 2002

For the period 4/01 to 7/01/2002, the total computed sediment discharge was 13764 tons, the mean daily sediment discharge was 149.61 tons. Applying the standard error for Eq (1) of 24.5 mg/liter to the computed sediment discharge of 13764 tons, the error bounds for the estimate are computed below.

Average discharge 4/01 through 7/01/2002 - $\text{mean}\left(Q_{CGRO}\right) = 1443\,\text{cfs}$

Standard error, Eq. (1) - $SSC_{SE} := 24.5 \cdot \frac{\text{mg}}{\text{liter}}$

Error bounds are +/- $1443 \cdot \text{cfs} \times 24.5 \cdot \frac{\text{mg}}{\text{liter}} \times 92 \cdot \text{day} = 8772\,\text{ton}$

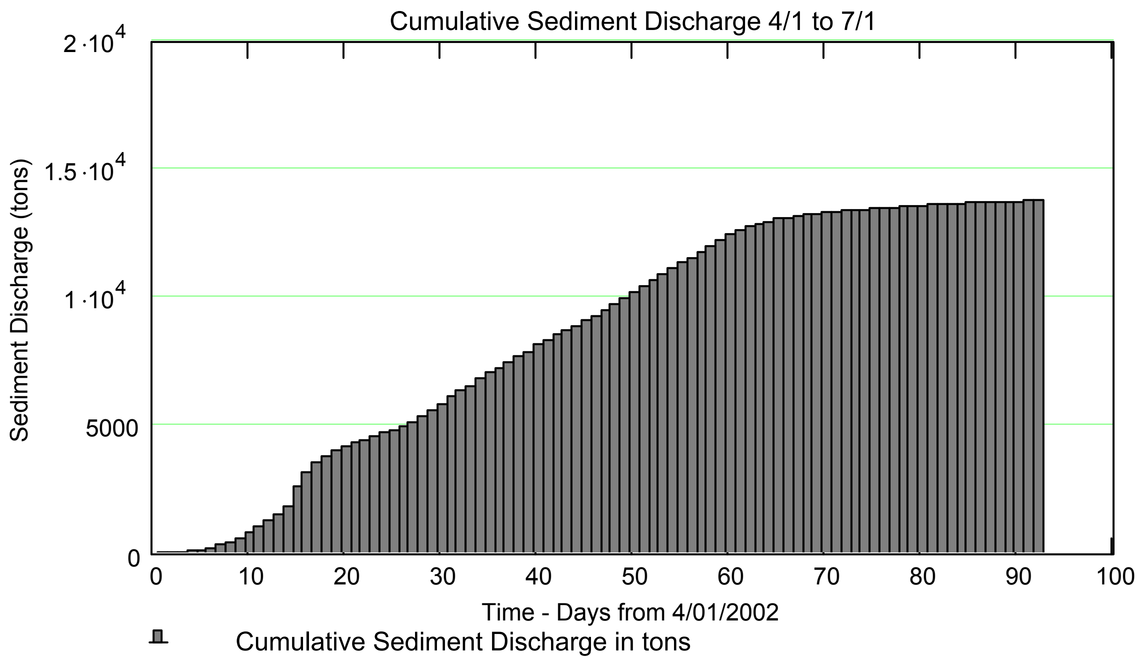

Figure 12 - Cumulative computed sediment discharge from Cougar reservoir in tons, April 1 to July 1, 2002

The estimated cumulative sediment discharge (Figure 12) between April 1 and July 1, 2002 is 13764 +/- 8772 tons or between 4992 and 22536 tons. Table 2 shows the computed daily mean SSC, computed daily mean sediment discharge, and the cumulative sediment discharge from April 1 to July 1, 2002.

Sample Calculations – SSC and Sediment discharge for May 10, 2002

Daily mean turbidity $T_{May10} := 107.50 \cdot NTU$

Daily mean discharge $Q_{May10} := 1716.10 \cdot cfs$ $\left(1716.10 \cdot \frac{ft^3}{sec}\right)$

Computed SSC using Eq (3) $SSC_{CGRO} = 1.90 \cdot T_{CGRO}^{0.752}$

$SSC_{May10} := 1.90 \times 107.50^{0.752}$ $1.90 \times 107.50^{0.752} \times \frac{mg}{liter} = 64.02842 \frac{mg}{liter}$

The computed daily mean SSC for May 1, 2002 is **64.03 mg/liter**

Computed sediment discharge for May 10, 2002 using Eq (5) $q_s = Q \times c_s \times 1day$

Convert daily mean discharge in cubic feet per second to cubic feet per day

$$1716.10 \cdot \frac{ft^3}{sec} \times 60 \cdot \frac{sec}{min} \times 60 \cdot \frac{min}{hr} \times 24 \cdot \frac{hr}{day} = 148271040 \frac{ft^3}{day}$$

Convert computed daily mean SSC in mg/liter to tons/cubic foot

$$64.02842 \cdot \frac{mg}{liter} \times 28.317 \cdot \frac{liter}{ft^3} \times 1.10231 \times 10^{-9} \cdot \frac{ton}{mg} = 1.99859 \times 10^{-6} \frac{ton}{ft^3}$$

Sediment discharge, q_s, is then computed:

$$q_s := 148271040 \cdot \frac{ft^3}{day} \times 1 \cdot day \times 1.99859 \times 10^{-6} \cdot \frac{ton}{ft^3}$$

$$q_s = 296.3\,ton$$

The computed sediment discharge for May 10, 2002 using Eq (3) and (5) is **296.3 tons**

Table 2 - Computed SSC, sediment discharge from Cougar Reservoir, April 1 to July 1, 2002

Date	Daily Mean Discharge (cfs)	Daily Mean Turbidity (NTU)	Computed Daily Mean SSC (mg/liter)	Computed Daily Mean q_s (tons)	Cumulative Computed q_s (tons)
01-Apr-02	2,013.7	1.2	2.18	11.8	11.8
02-Apr-02	1,669.0	1.9	3.08	13.9	25.7
03-Apr-02	1,770.0	2.4	3.67	17.5	43.2
04-Apr-02	2,239.7	6.6	7.85	47.4	90.6
05-Apr-02	2,576.8	7.4	8.56	59.5	150.1
06-Apr-02	2,387.6	12.6	12.77	82.2	232.4
07-Apr-02	2,447.7	12.8	12.92	85.3	317.7
08-Apr-02	2,125.4	17.8	16.56	94.9	412.6
09-Apr-02	2,190.4	38.5	29.58	174.7	587.3
10-Apr-02	3,548.9	33.9	26.88	257.3	844.6
11-Apr-02	3,462.2	31.6	25.50	238.1	1082.7
12-Apr-02	3,000.7	31.4	25.38	205.4	1288.1
13-Apr-02	2,839.0	39.2	29.99	229.6	1517.7
14-Apr-02	2,290.3	72.7	47.71	294.7	1812.4
15-Apr-02	4,592.1	112.7	66.34	821.6	2634.0
16-Apr-02	3,619.5	91.4	56.67	553.2	3187.2
17-Apr-02	2,916.1	68.7	45.72	359.6	3546.8
18-Apr-02	2,516.0	53.5	37.89	257.1	3803.9
19-Apr-02	2,217.2	41.4	31.24	186.8	3990.7
20-Apr-02	2,085.2	36.6	28.48	160.1	4150.8
21-Apr-02	1,899.3	37.1	28.77	147.4	4298.2
22-Apr-02	1,823.9	36.1	28.18	138.6	4436.8
23-Apr-02	1,813.5	33.8	26.82	131.2	4568.0
24-Apr-02	1,753.9	31.6	25.50	120.6	4688.6
25-Apr-02	1,679.4	31.6	25.50	115.5	4804.1
26-Apr-02	1,688.7	35.6	27.89	127.0	4931.1
27-Apr-02	1,729.8	51.8	36.98	172.5	5103.6
28-Apr-02	1,598.3	95.0	58.34	251.5	5355.1
29-Apr-02	1,564.4	77.9	50.26	212.0	5567.1
30-Apr-02	1,583.5	105.9	63.31	270.4	5837.5
01-May-02	1,620.4	95.9	58.76	256.8	6094.3
02-May-02	1,656.3	84.2	53.28	238.0	6332.3
03-May-02	1,667.3	79.4	50.98	229.2	6561.5
04-May-02	1,634.9	90.3	56.16	247.6	6809.2
05-May-02	1,517.6	88.3	55.22	226.0	7035.2
06-May-02	1,466.0	91.8	56.86	224.8	7260.0
07-May-02	1,374.0	102.2	61.64	228.4	7488.4
08-May-02	1,286.8	99.4	60.37	209.5	7697.9
09-May-02	894.9	99.6	60.46	145.9	7843.8
10-May-02	1,716.1	107.5	64.03	296.3	8140.1
11-May-02	1,164.0	101.7	61.41	192.8	8332.9
12-May-02	1,185.3	95.7	58.67	187.5	8520.4
13-May-02	1,261.9	86.9	54.56	185.7	8706.1
14-May-02	1,281.7	85.8	54.04	186.8	8892.9
15-May-02	1,297.6	87.2	54.70	191.4	9084.4
16-May-02	1,299.5	89.8	55.93	196.0	9280.4

Date	Daily Mean Discharge (cfs)	Daily Mean Turbidity (NTU)	Computed Daily Mean SSC (mg/liter)	Computed Daily Mean q_s (tons)	Cumulative Computed q_s (tons)
17-May-02	1,306.2	92.7	57.28	201.8	9482.1
18-May-02	1,403.0	94.0	57.88	219.0	9701.2
19-May-02	1,397.9	106.2	63.45	239.2	9940.3
20-May-02	1,343.1	110.0	65.14	236.0	10176.3
21-May-02	1,306.8	124.3	71.42	251.7	10428.0
22-May-02	1,284.3	133.8	75.48	261.4	10689.4
23-May-02	1,208.8	122.7	70.72	230.6	10920.0
24-May-02	1,213.8	109.0	64.70	211.8	11131.8
25-May-02	1,208.5	106.3	63.49	206.9	11338.7
26-May-02	1,220.6	115.3	67.49	222.2	11560.9
27-May-02	1,220.7	112.1	66.08	217.5	11778.4
28-May-02	1,370.9	97.7	59.59	220.3	11998.7
29-May-02	1,560.4	98.0	59.72	251.3	12250.1
30-May-02	1,579.4	81.9	52.18	222.3	12472.3
31-May-02	1,405.1	65.9	44.32	167.9	12640.3
01-Jun-02	1,312.2	53.8	38.05	134.6	12774.9
02-Jun-02	1,124.5	45.8	33.71	102.2	12877.1
03-Jun-02	1,095.6	40.6	30.79	91.0	12968.1
04-Jun-02	991.1	38.4	29.52	78.9	13047.0
05-Jun-02	995.5	34.4	27.18	73.0	13120.0
06-Jun-02	999.6	31.6	25.50	68.7	13188.7
07-Jun-02	871.7	26.3	22.21	52.2	13240.9
08-Jun-02	753.9	22.5	19.75	40.2	13281.1
09-Jun-02	697.9	20.6	18.48	34.8	13315.9
10-Jun-02	607.1	18.1	16.77	27.5	13343.3
11-Jun-02	626.0	16.5	15.64	26.4	13369.7
12-Jun-02	641.1	16.1	15.36	26.6	13396.3
13-Jun-02	654.4	15.2	14.71	26.0	13422.3
14-Jun-02	719.9	14.0	13.82	26.8	13449.1
15-Jun-02	702.4	12.4	12.62	23.9	13473.0
16-Jun-02	596.8	11.2	11.69	18.8	13491.8
17-Jun-02	607.0	24.2	20.86	34.2	13526.0
18-Jun-02	840.0	19.2	17.53	39.7	13565.7
19-Jun-02	675.2	15.8	15.14	27.6	13593.2
20-Jun-02	559.9	13.9	13.75	20.8	13614.0
21-Jun-02	551.8	13.2	13.23	19.7	13633.7
22-Jun-02	518.5	13.3	13.30	18.6	13652.3
23-Jun-02	450.9	12.2	12.47	15.2	13667.4
24-Jun-02	439.0	11.1	11.61	13.7	13681.2
25-Jun-02	449.7	11.2	11.69	14.2	13695.4
26-Jun-02	426.3	10.8	11.37	13.1	13708.4
27-Jun-02	352.4	10.2	10.89	10.4	13718.8
28-Jun-02	336.6	9.7	10.49	9.5	13728.3
29-Jun-02	415.6	10.0	10.73	12.0	13740.4
30-Jun-02	427.5	10.4	11.06	12.7	13753.1
01-Jul-02	326.4	12.0	12.31	10.8	13763.9

DECEMBER 2002 – JANUARY 2003 OBSERVED TURBIDITY

The 1400 foot residual pool has been maintained through the fall and winter. The weather pattern produced several storms which raised the reservoir elevation to 1411 feet on December 31st and 1413 feet on January 5th. The highest turbidity occurred on December 31st at 202 NTU. Turbidity levels rose again and reached 117 and 113 NTU on January 3rd and 5th respectively. The sharp increases in turbidity were due to erosion at the 1405 to 1411 foot level in the reservoir and increased turbid inflows from the tributaries draining the reservoir. Turbidity levels quickly dropped when the reservoir releases were sharply increased to bring the reservoir pool back to the 1400-foot level. Figure 13 shows the observed reservoir elevation plotted against the observed flow and turbidity downstream at the USGS gage near Rainbow, OR.

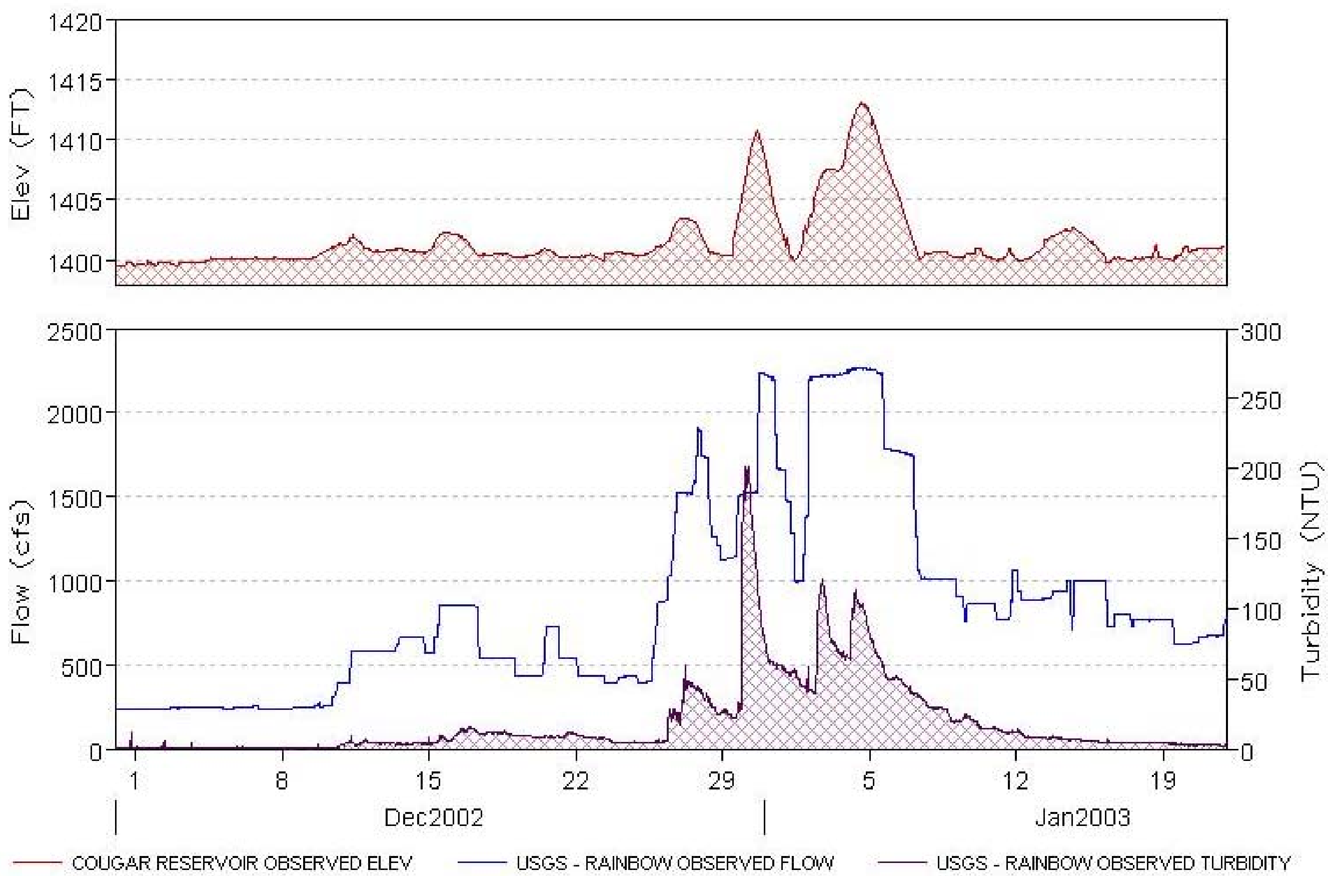

Figure 13 - Observed Cougar Reservoir elevation December 2002 - January 2003. Observed discharge and turbidity USGS gage 14159500 SF McKenzie near Rainbow, OR

SEDIMENT GRAIN SIZE CLASSIFICATION - TERMINOLOGY

Particle size is the most significant physical property of sediment. Sediment particles are classified, based on their size, into six general categories: *Clay, Silt, Sand, Gravel, Cobbles,* and *Boulder*s. Because such classifications are essentially arbitrary, many grading systems are to be found in the engineering and geologic literature. Table 3 shows a grade scale proposed by the subcommittee on Sediment Terminology of the American Geophysical Union. This scale is adopted for sediment work because the sizes are arranged in a geometric series with a ratio of two. (O'Brien, 2000)

Table 3 - American Geophysical Union Sediment Classification System (USACE EM-1110-2-4000)

	Sediment Size Range		
Sediment	millimeters	microns	Inches
Very large boulders	4096 - 2048		160-80
Large cobbles	256 - 128		80-40
Medium boulders	1024 - 512		40-20
Small boulders	512 - 256		20-10
Large cobbles	256-128		10-5
Small cobbles	128-64		5-2.5
Very coarse gravel	64-32		2.5-1.3
Coarse gravel	32 - 16		1.3-0.6
Medium gravel	16 - 8		0.6-0.3
Fine gravel	8 - 4		0.3-0.16
Very fine gravel	4 - 2		0.16-0.08
Very coarse sand	2.0 - 1.0	2000-1000	
Coarse sand	1.0 - 0.5	1000-500	
Medium sand	0.5 - 0.25	500-250	
Fine sand	0.25 - 0.125	250-125	
Very fine sand	0.125 - 0.062	125-62	
Coarse silt	0.062 - 0.031	62-31	
Medium silt	0.031 - 0.016	31-16	
Fine silt	0.016 - 0.008	16-8	
Very fine silt	0.008 - 0.004	8-4	
Coarse clay	0.004 - 0.002	4-2	
Medium clay	0.002 - 0.001	2-1	
Fine clay	0.0010 - 0.0005	1.0 - 0.5	
Very fine clay	0.0005 - 0.00024	0.5 - 0.24	

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SOFTWARE USED

Calculations made using *Mathcad 2001i Professional*, © 1986-2001 MathSoft Engineering & Education, Inc.